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IS&T Approaches to Reducing the Cost Of Satellite Constellations

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TOPICS

- Introduction
- Summary
- What's the Problem?
  - Constellations are Useful
  - Constellations are Too Expensive
    - On-Orbit Experience Has Demonstrated This
- What Can IS&T Do About It?
  - Constellation Management
  - Reducing Operations Cost
  - Reducing Flight Systems Cost
- Conclusions

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INTRODUCTION

- **Jim Wertz**
  - **President of Microcosm, a small aerospace business in El Segundo, CA**
  - **Worked for CSC doing Attitude Analysis for GSFC (thousands of years ago)**
  - **Editor and principal author of *Spacecraft Attitude Determination and Control* (1978), *Space Mission Analysis and Design* (1989, 1991, 1999), *Reducing Space Mission Cost* (1996), and *Spacecraft Orbit and Attitude Systems* (in press)**
  - **Teach courses in the above topics, including "Constellation, Design, Management, and Economics" (CDM&E) at GSFC in November, 2000**
  - **Not an operator, not an IS&T professional, and don't build constellations, so I'm equally qualified in all aspects of today's topic**
- **Microcosm**
  - **Scorpius Low Cost Launch Vehicle program**
  - **Autonomous navigation and orbit control systems**
  - **Systems and mission engineering**
- **This talk drawn largely from the CDM&E course**
  - **Based on the experience of the world satellite community**
  - **Includes our own experience in constellation design and flying both autonomous navigation and autonomous orbit control systems**

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EXECUTIVE SUMMARY

- **The fundamental problem is that constellations are potentially remarkably useful but cost far too much**
  - **Costs are too high in all areas -- non-recurring, manufacturing, launch, and operations**
  - **Iridium was sold for 0.5% of the cost to build it**
- **Constellations, like most spacecraft, are fundamentally data oriented**
  - **May generate data (e.g., Earth observations) or simply move it from place to place (e.g., telephone or data systems)**
  - **Applies to both constellation control and payload data**
  - **From a mission engineering perspective, constellation management and payload data management are the keys to a successful, low-cost system**
    - **We will focus here principally on <u>constellation management</u>**
  - **Very low cost constellations are possible (ORBCOMM almost got there), but they require changing the way we do business in space**

Constellations are fundamentally information systems. Thus, it is the IS&T community's responsibility to ensure that such systems meet their objectives at minimum cost and risk.

What's the Problem?

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CONSTELLATIONS ARE USED FOR MULTIPLE APPLICATIONS

- **Typical constellation applications:**

Application	Example	Coverage	Comments
Communications:			
GEO Comm Sats	TDRS *	LEO orbits	Replaces NASA network
Little LEO	ORBCOMM	Near-continuous	Store and Forward messaging
Big LEO	Iridium	Continuous	Telephone—now bankrupt
Broadband	Teledesic	Redundant	“InterNet in the Sky”
Navigation	GPS	4-fold continuous	DoD funded; high civilian usage
	GLONASS	4-fold continuous	Russian equivalent to GPS
Weather	DMSP	Intermittent	Most weather sats in GEO
Surveillance	DSP	Continuous	At GEO
	NDS	Continuous	On GPS satellites
Sampling	Cluster †	4-fold sampling	Geomagnetic time variations
	MAGCON	Multi-fold sampling	Geomagnetic Structure and Evolution
Interferometry	TechSat-21	TBD	Constellation of formations

*TDRS-A lost on Challenger disaster
†First Cluster constellation lost on first launch of Ariane 5

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POLITICAL AND ECONOMIC REALITIES OF CONSTELLATIONS

- Historically, constellations have proven to be expensive and have taken longer to implement than planned
- Difficult to gain financial or political support to build the full system
  - Government example: GPS did not have sufficient political support to get funded; needed to add NDS payload to make the constellation real
    - GPS took nearly 10 years to build up the constellation
  - Commercial examples: Raising the necessary capital is difficult and time consuming
    - With Iridium, ICO, and GlobalStar it will get harder
- Cutting cost is difficult
  - Cutting the number of spacecraft in a 50 satellite constellation by 20% reduces the space segment cost by 15% to 17% and the system cost by 8% to 12%
  - Delays are dramatically expensive for commercial programs due to the cost of money
  - Little room to negotiate dramatically lower launch costs
- Reducing non-recurring development cost often drives up operations costs by substantially more

CONSTELLATIONS ARE A BUSINESS

- **Commercial constellations**
  - **Fundamental characteristic is that they must provide adequate return on investment to warrant an inherently risky investment**
    - **This means they must take in <u>substantially</u> more than they cost**
  - **If commercial constellations continuously lose money, there will be no more commercial investment capital available**
- **Scientific or military constellations**
  - **Do not have the same severe financial constraints of commercial constellations**
  - **Do not carry the same level of national prestige as the manned program or interplanetary exploration**
  - **Must be perceived as worth the investment to justify an inherently high cost**
    - **GPS did not have sufficient support to be funded without the NDS on board**
- **Constellations are dramatically expensive**
  - **Engineering costs: NRE, spacecraft, launch, ground segment, and operations**
  - **Financial costs: Cost of money, licensing, agreements, cost of sales, risk reduction**
    - **Financial costs can double the cost of a commercial constellation**

In constellation systems engineering, we cannot ignore business and financial considerations.

- **The Iridium constellation has been one of the most publicized bankruptcies in recent years and, therefore, provides a rich set of "lessons learned"**

THE IRIDIUM EXPERIENCE

- **Several cautionary notes:**
  - **Iridium financial data has not been made public—cost estimates are only approximations**
  - **Iridium had strong, competent systems engineering and did many things right**
    - **Launched the satellites before the software was done to cut a year off the system schedule (an excellent choice)**
    - **Developed satellite manufacturing techniques that allowed them to turn out satellites at more than 1 per week (See SMAD III, Sec. 19.1 for a detailed discussion)**

Metric	Traditional Approach	Multi-Satellite Approach
Spacecraft Cost	$66K/kg	$20K/kg
Integration Time	225 days	24 days
Build-to-launch Time	18 months	2 months
Production Rate	> 6 months/Sat	< 1 week/Sat

- **Iridium truly challenged the paradigm of how to develop satellite systems**

> **To learn from the Iridium experience, we need to try to distinguish what was done badly from what was done well—both extremes occurred.**

- **Iridium was originally designed with 77 satellites, but was later reduced to 66 to reduce cost**
  - **Full constellation was launched in 13 months, with no launch failures**
- **Filed for bankruptcy, August, 1999, after defaulting on $1.55B in bank loans**

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SOME OF THE IRIDIUM ”KNOWNS”

- **System cost was over $5 billion with 5 year life**
- **Initial pricing was about $3000/phone and $7/minute, later dropped to $3/minute and lower**
- **Finances for January, 2000 (from *Satellite Finance*, 3/8/00):**
  - **Customers — 50,000**
  - **Revenue — $1.5 Million ($30/month/customer)**
  - **Expenses — $110.5 Million**
  - **Reported loss — $112.6 Million**
- **In March, 2000, Iridium got a $3 million loan to continue operation—lasted 11 days**
  - **Implies operations cost of $2 million/week, $100 million/<u>year with all payload operations fully automated on board</u>**
- **March, 2001—System sold for $25 million**
  - **Has a $73 million multi-year DoD contract and is still operational**
  - **Original investors lost $5 billion**

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IRIDIUM FINANCIAL CALCULATIONS

- **Amortization estimate**
  - — **Basis = $5 billion development, 5 year life, 10% interest**

- **Results of amortization analysis**

— **Total cost**	**$6.59 billion**
— **Total interest**	**$1.59 billion**
— **Amortization cost**	**$110 million/month**
— **Interest only cost**	**$42 million/month**

- **Operations cost of $8 million to $10 million/month**
  - — **All payload functions automated on-board**
  - — **These costs are after bankruptcy with very little activity going on**
  - — **Had spent 2 years automating the ground operations to the greatest possible extent**
  - — **Operations team size**
    - **Initially 20–30 people per spacecraft**
    - **Down to 6 people per spacecraft after 1 year**
    - **Down to total of ~100 people after 2 years**
  - — **Initial objective was to operate the system with a total team of 6 people**

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SUMMARY OF THE PROBLEM

- **Constellations offer enormous promise for new capabilities in space**
- **Space systems are inherently expensive -- constellations are more so, and the high cost is often underestimated**
- **Key "lessons learned" from past experience:**
  - **Must emphasize life-cycle cost**
    - * **Non-recurring development, recurring manufacturing, and operations must all be addressed during the entire process**
    - * **Early non-recurring costs are "expensive," but pushing these costs downstream to operations can be even more expensive**
      - **Space Shuttle sold on the basis of dramatically reducing launch costs**
      - **GPS and Iridium operations costs much higher than planned**
  - **Must be willing to compromise between what you want and what you can afford**
    - * **Hard to do in a traditional requirements-driven program**
  - **Must have strong, cost-conscious, up-front systems engineering**

Ignorance is rarely of value in improving performance or reducing cost.

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What Can IS&T Do About It?

- Constellation Management
- Reducing Operations Cost
- Reducing Flight Systems Cost

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THE "TALL TELEPHONE POLE" PROBLEM

- **A key paradigm in LEO communications constellations is to think of the satellites themselves as "just tall telephone poles"**
  - **This analogy is repeated often throughout the community**
  - **Useful for conveying the fact that the real business issues are not related to the satellites but rather to what they do and what information they obtain or transmit**
- **Unfortunately, these telephone poles are moving at 8 km/sec with respect to each other and the user and require significant and continuing maintenance**
  - **With the telephone pole analogy, it's easy to forget that there is a complex task of constellation management**
  - **Iridium automated nearly all of its payload operations functions on board and had planned on running the constellation operations with a team of 6 people**
    - **Early in the program, they were using a team of 600 people**
  - **Constellation Management should be thought of as a key <u>systems level</u> IS&T issue**
  - **May be implemented on board, on the ground, or a mix of both**
  - **Key is the minimize the cost and complexity of the system as a whole**

Constellation Management is a key component of containing or reducing cost.

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SUMMARY OF KEY CONSTELLATION MANAGEMENT ISSUES

Issue	Potential Problem Areas	Trades, Issues, and Comments
Initial System Deployment	Create useful pattern with only a few sats	Can rephase within each plane at very low cost
Final System Deployment	Get full operational capability as soon as possible	Sequence likely to depend on launch vehicle selection
Coverage	Typically an operational requirement to maintain	Maintained by long-term stationkeeping process
Operations	Historically high cost & cost risk	Easy to underestimate complexity of multi-satellite operations
Planning and Scheduling	Major cost element; 50% of Operations activity for Iridium	Made much easier by absolute stationkeeping
Stationkeeping	Very Operations intensive; risk of errors	Automate on board to minimize cost and risk
Collision Avoid. (internal)	Risk of collision cascade	Design and manage for near-absolute collision avoidance
Collision Avoid. (external)	Advance warning may be short	Maximize warning/planning time; coordinate with potential competitors
RF interference	May cause service outages	Minimized by adv. knowledge
Propellant management	Use of consumable limits life	Relative stationkeeping does <u>not</u> minimize propellant

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SUMMARY OF KEY CONSTELLATION MANAGEMENT ISSUES (CONT)

Issue	Potential Problem Areas	Trades, Issues, and Comments
Higher order harmonics	Small period diff's in each plane cause constell. to decay	All sats need to have identical average period
Resource utilization	Expensive resource needs to be used efficiently	Continuous search for new applications and users
Sparing approach	Need rapid regeneration of full service capability	Trade is on-orbit spares vs. ground spares with rapid launch capability
Satellite Loss	Causes periodic service outage; worst near equator	Need plan for covering outage hole with existing satellites
Satellite replacement	Needs to done as promptly as possible	Quick typically means heavy fuel usage which limits later life
Spacecraft Disposal	Need to remove from constellation pattern	Deorbit from LEO; MEO can be a problem; Raise 500 km in GEO
Technology upgrades	Avoiding technological obsolescence	Do as much in software as possible; have very large computer margin
Expansion of service	Need to keep service responsive to demand	Adding satellites to existing pattern would be advantageous
Phase-in of next generation	Create smooth transition to bigger, better system	Requires significant logistic planning
System end-of-life	Major liability may remain	How to realistically close down activity or transition assets

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CONSTELLATION MANAGEMENT EXAMPLE: THE NEED FOR STATIONKEEPING

- **System objective is to maintain the same <u>relative</u> position among the satellites in a constellation**
  - **Want to minimize propellant usage to do this**
  - **Want to minimize system cost and complexity**
- **Need for stationkeeping arises for three sources**
  - **Atmospheric drag will eventually bring down a LEO constellation**
  - **Other orbit perturbations result in differential satellite motion that accumulate over time**
  - **Variations in initial conditions for each satellite cause differential drift**
- **In general, can treat each perturbation separately in deciding how best to deal with it**
  - **Major perturbations should be addressed individually**
  - **Minor perturbations can be lumped into the overall budget**
- **Ultimate implementation will be divided into two major categories of in-track and cross-track (= control of the orbit plane)**
- **GEO stationkeeping is well-understood and treated in most standard texts—we will concentrate on LEO stationkeeping**

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MAIN STATIONKEEPING TRADES

- **The two major stationkeeping trades are interrelated**
  - **Whether to maintain the system altitude or allow the constellation to slowly "fall" to lower altitudes due to drag**
  - **Whether to maintain an <u>absolute pattern</u> or maintain only the <u>relative</u> <u>locations</u> of all satellites**

- **Allowing the system to fall reduces propellant requirement only in the short term (i.e., until you want to restore the altitude)**
  - **Replacement satellites would be launched at the lower altitude**
  - **Drag would continually increase as the altitude decreases**
  - **Coverage holes would appear as the altitude decreases**
  - **Results in an ever changing constellation pattern with continuous analysis and intensive operations**

- **Maintaining the altitude is the only way to give the system long-term stability without having performance degradation grow with time**

Normally, the system altitude should be maintained over the long term for an Earth-oriented constellation

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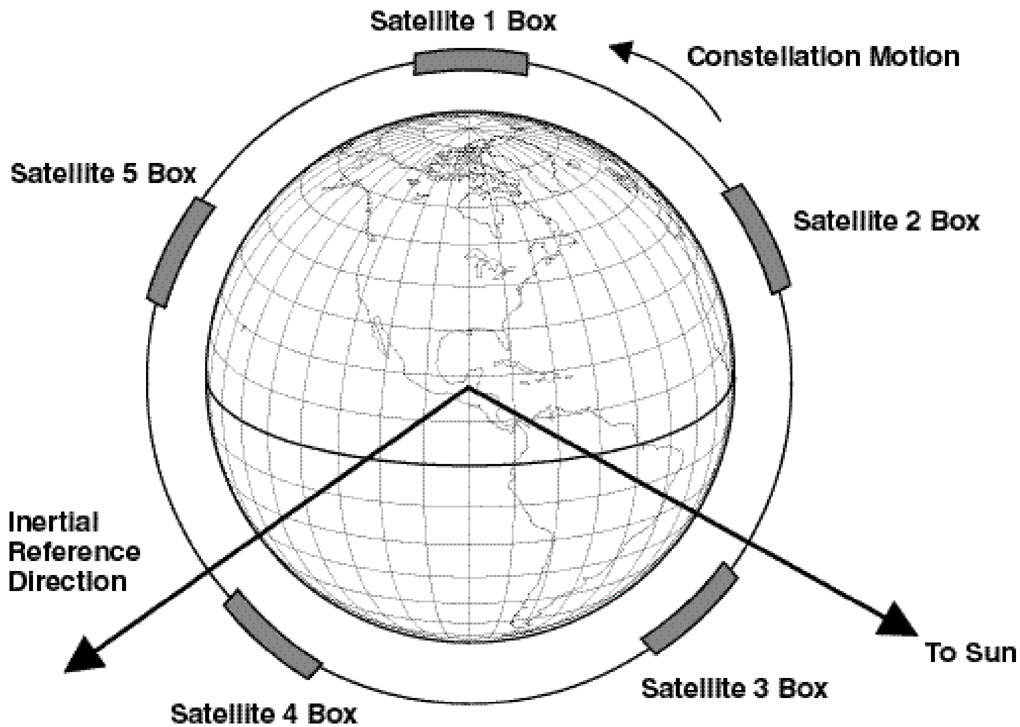
ABSOLUTE STATIONKEEPING MAINTAINS EACH SATELLITE WITHIN A PRE-DEFINED MATHEMATICAL BOX



- Boxes are equivalent to stationkeeping boxes in GEO, except that they are moving with respect to the surface of the Earth
  - — Results in a predetermined, "static" constellation
- In relative stationkeeping only the relative positions of the boxes are maintained

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RELATIVE VS ABSOLUTE STATIONKEEPING

- If decision to maintain altitude is made, then there is no propellant advantage to "relative" stationkeeping and may be some disadvantage
- Inherent complexity of "relative stationkeeping" represents high operations cost, very complex stationkeeping logic, and the potential danger for satellite collisions
  - — Example: Recent paper by Draper Labs on using genetic algorithms for stationkeeping used 12–24 hours on 6 parallel processors (SG workstation) to optimize 4 burns for 1 satellite over 90 days with atmosphere fully known in advance
- To minimize propellant usage, what we want to do is to just put back the energy removed from the system by drag
- Can combine minimum propellant usage with absolute stationkeeping
  - — Relative stationkeeping may use more propellant due to need to space out maneuvers
- Absolute stationkeeping greatly simplifies constellation build-up—just put satellites in their assigned slots and begin orbit maintenance

Relative stationkeeping attempts to minimize propellant usage, but the problem is simple physics—we must put back the delta V the atmosphere takes out

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SECONDARY BENEFITS OF ABSOLUTE STATIONKEEPING

- Constellation is deterministic
  - Intended position of each satellite at all future times is known
  - Could today determine (or set) the time of station passage for any particular satellite in the constellation on any day in any future year
  - Makes constellation planning and scheduling easier
  - Each successive satellite will be put into its assigned place at the time of launch
  - Basic geometrical conditions (sun cycle, ground station angle) are fully known in advance
- Pattern is deterministic
  - Can assign a specific ground coverage pattern
  - Can pre-establish pattern boundaries as a function of time
- Makes job of spacecraft requirements specification easier
  - Spacecraft simply needs to meet the preassigned ground coverage pattern
  - May reduce amount, weight, and cost of spacecraft components
    - May eliminate need for gyros
    - Reduces maximum disturbance torque
    - Uses smaller thrusters
- Reduces operations complexity by allowing burns to occur at any time

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ON-BOARD VS. GROUND BASED STATIONKEEPING

Traditional orbit control strategies are ground based

- **Commands are computed on the ground, verified, uploaded, verified, executed and the results are verified**
- **Activity is operations intensive and, therefore, expensive and entails risk**
- **Objective is to maximize the time between orbit maneuvers**
  - **Typically requires separate stationkeeping mode that may halt operations**
  - **Results in a relatively large impulse compared to autonomous orbit control**

- **Autonomous control uses on-board logic to control the satellite orbit, just as the attitude control system uses on-board logic to control the orientation**
  - **Orbit control is far safer than attitude control with less risk of catastrophic failure**
  - **Total ΔV over the satellite life is determined by atmospheric drag**
  - **The process of orbit control simply adjusts the size and timing of the burns to more precisely negate the effect of drag**
  - **Minimizing the number of burns is not required**
- **More frequent small burns actually improves performance, minimizes propellant usage, and minimizes disturbance to the spacecraft**
- **Comparable to on-board vs. ground-based attitude control**

Compared to ground-based control, autonomous on-board orbit control can improve performance and reliability and reduce both non-recurring and recurring cost.

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AUTONOMOUS STATIONKEEPING IMPLEMENTATION

- In September, 1999, Microcosm demonstrated the first absolute on-board orbit control system on the UoSAT-12 spacecraft in a circular, 650 km orbit
  - System is called the Orbit Control Kit (OCK)
  - OCK used an SSTL GPS receiver for input and sent commands to the Attitude Control System using nitrogen cold gas thrusters
  - Data was collected continuously, but no commanding was done to OCK during the 30-day test period
  - During the previous 90 days, UoSAT-12 without any orbit maintenance had slipped approximately 4500 km in In-Track position
  - The OCK software was created on two Phase II SBIRs from the Air Force Research Laboratory (AFRL)

Microcosm is actively marketing this technology to the astronautics community.

- Autonomous stationkeeping also under development at GSFC

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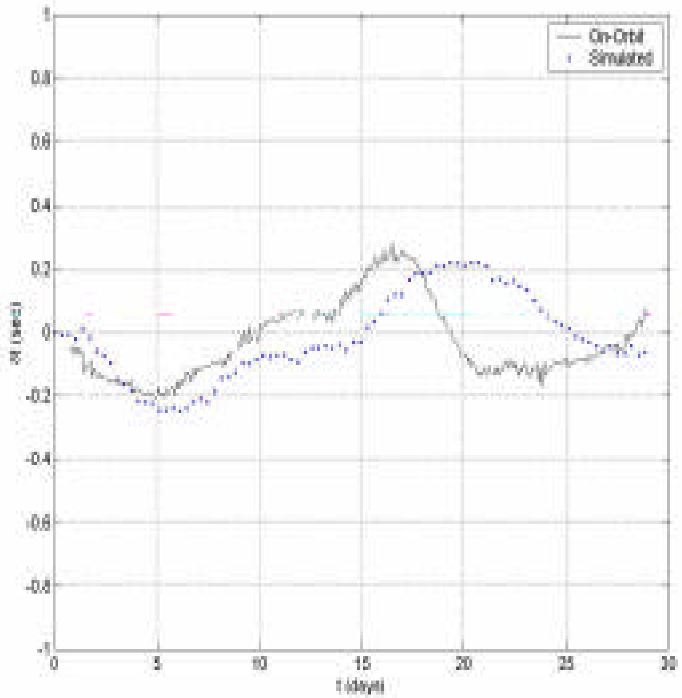
SIMULATION RESULTS VS. ON-ORBIT PERFORMANCE

	On-Orbit	Simulation
Atmosphere	Real	MSIS
F10.7	Real	Measured
Duration (days)	29	29
Performance (sec, 1σ)	± 0.12	± 0.14
Performance (km, 1σ)	± 0.9	± 1.02
No. of Burns	53	48
Maximum burn (mm/s)	2.7	4.9
Minimum burn (mm/s)	0.053	0.19
Mean burn (mm/s)	1.4	1.6
Sum of burns (mm/s)	73.3	76.3
ΔV to restore altitude	85–100 mm/s	



System simulation closely models performance and total ΔV requirements. Simulation results show OCK saving 10% ΔV relative to traditional monthly altitude restoration.

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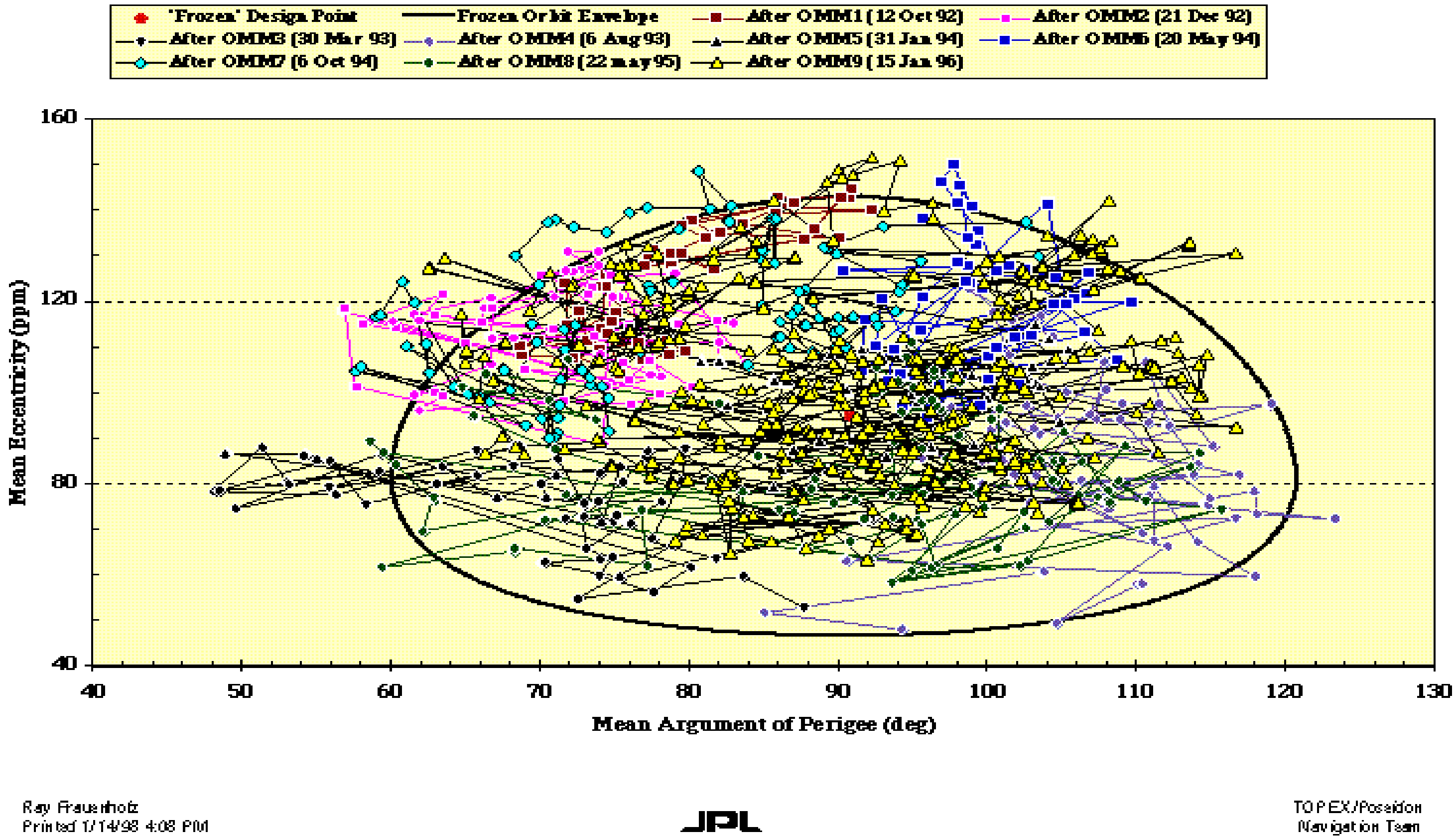
TOPEX CONTROL OF ECCENTRICITY AND ARGUMENT OF PERIGEE

Mean Eccentricity Vector
(as of 11 Jan '98)



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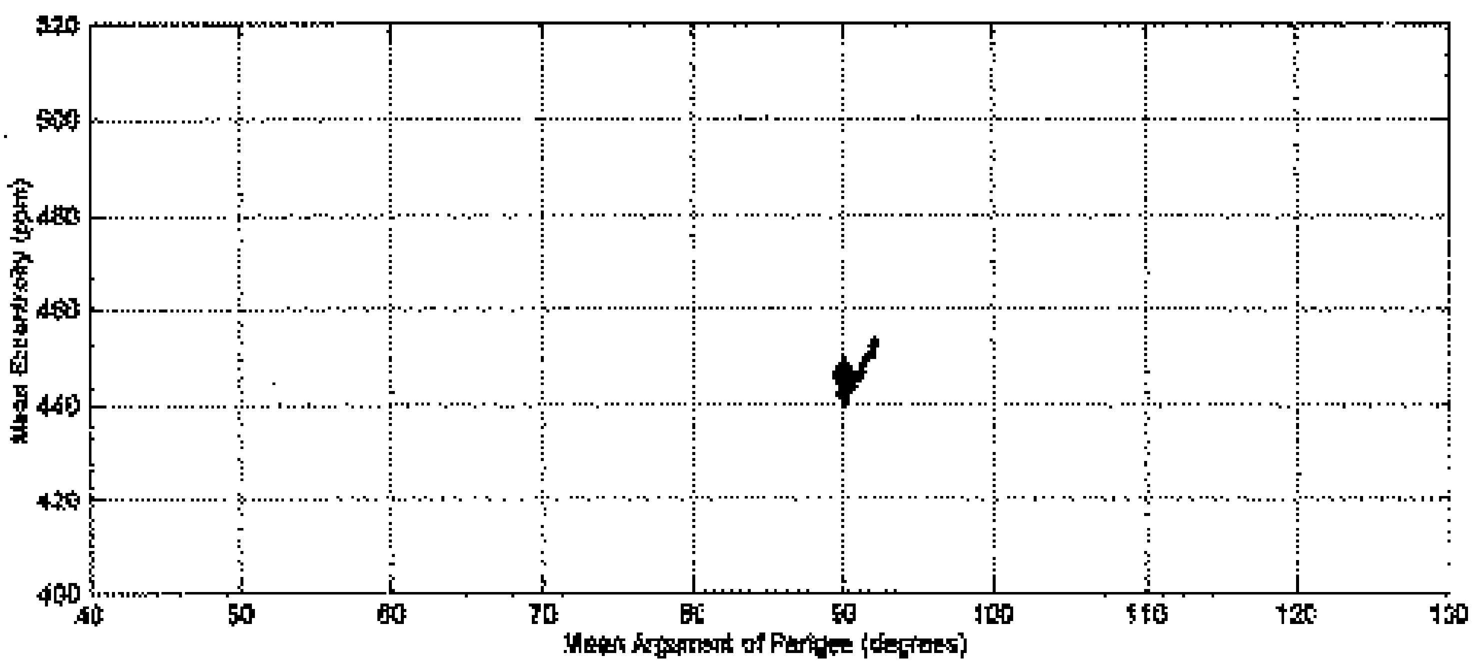
AUTONOMOUS ORBIT CONTROL RESULTS, TOPEX ECCENTRICITY AND ARGUMENT OF PERIGEE

- **Graph below shows results using autonomous orbit control for 6 months on the same scale as the previous TOPEX results—TOPEX at higher altitude (1300 km) with less drag than the simulation (650 nm)**
- **TOPEX orbit control operations (one spacecraft) required approximately 2 full-time people for the life of the mission (maneuvers done at 3–6 month intervals)**
- **Autonomous orbit control maneuvers done every 2–4 days (at 650 km altitude) with no ground control and using less total propellant than maneuvers done less frequently**



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CONSTELLATION OPERATIONS

- In many cases, constellation operations have proven to be significantly more expensive than anticipated
  - Most cost data is proprietary, but some is known
  - Anecdotal evidence suggests that several constellations significantly exceeded planned operations costs
- DoD mission operations costs are approximately $1 billion/year
  - Principal constellation is GPS
- As discussed aove, Iridium had planned to be operated with a crew of 6 people
  - Had at least 600 people early in the program
  - Dropped to about 100 people after 2 years of expensive work on automating ground operations
  - Operations crew was about 100 at the time of the decision to deorbit the system
    - Followed 2 years of extensive work on automating the operations activity
    - Approximately half the work load was planning and scheduling
    - Approximately 10% was navigation and orbit control
  - In March, 2000, a $3 million loan to continue operations lasted 11 days
    - Implies operations costs of approx. $2 million/week or $100 million/year

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RECOMMENDATIONS FOR REDUCING COST OF CONSTELLATION OPERATIONS

Remember that running a multi-satellite constellation is complex and expensive

- ¾ **It requires significant planning and consideration during mission design**
- ¾ **Putting off dealing with operations issues can dramatically drive up down-stream costs**

· **Automate repetitive functions, doing as much as possible on board**

- ¾ **Functions to automate on board**
  - **Attitude and orbit control**
  - **Power management and thermal control**
  - **Payload monitoring control**
- ¾ **Functions where personnel are key (i.e., use automation to help, not <u>do</u>)**
  - **Monitoring and exception handling**
  - **Planning and scheduling**
  - **Looking for new applications and users**

· **Allow each satellite to be handled differently**

- ¾ **Each satellite behaves as an individual**

Remember that these "tall telephone poles" are complex and expensive to erect, maintain and replace.

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REDUCING FLIGHT SYSTEMS COST

- **Space systems, particularly constellations, will become more software dominated in the future**
  - **Both inevitable and, in most cases, desirable**
  - **Has the potential to dramatically increase performance and reduce cost**
- **<u>Warning: The highest levels of autonomy are found in the lowest cost and highest cost systems</u>**
  - **In low cost systems, because there isn't enough money to support full-time operations**
  - **In the highest cost systems for technical reasons**
  - **Is your systems automated in order to reduce cost or to create the most complex data system known to mankind?**
- **Want to think of the spacecraft + the ground as a large data management and decision making system**
  - **What is the lowest cost, most reliable approach to getting decisions made, creating or obtaining data, and getting that data where it's needed?**

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KEY FLIGHT SYSTEMS COST ISSUES

- **The introduction of software dominated space systems will create a multitude of new and exciting failure modes**

- **Other things being equal, it's best to solve as many of these problems beforehand as possible**
  - **Testability and an extensive test program are key**
    - **Just like hardware -- test it like it flies**
  - **In any system processing real data, mathematical singularities will absolutely occur**
    - **The system <u>will</u> divide by 0 and take the arc sin of a number greater than 1**
    - **Be prepared to handle these**
  - **<u>Time on board a spacecraft is discontinuous</u>**
    - **Time jumps and negative time flow make many data systems behave badly -- plan for them to occur**

- **<u>On-orbit reprogrammability is an absolute requirement</u>**
  - **Software is the one component that can be updated on orbit at very low cost**
  - **Must have the operational procedures in place to do this**
  - **At launch, should have twice the memory and throughput that is being used**

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Conclusions

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FIRST LESSON IN REDUCING COST

- If we are going to successfully reduce cost, we have to talk about real cost and make cost data known.
- There is a very strong tendency not to want to do this
  - Cost and price data is sensitive and much of it is proprietary
  - Cost data is exceptionally hard to compare across programs and components
    - Program data may include or exclude elements such as launch, ground station, operations, infrastructure cost, etc.
    - Component cost depends far more on how something is bought rather than what is bought
  - Cost data is frequently hidden to make costs appear lower
    - Costs buried in infrastructure cost
    - May or may not include non-recurring
    - Example: Virtually unknown what a Space Shuttle launch actually costs
- Revealing costs may make it harder to get a program funded; nonetheless,

Reducing space mission cost is hard if we know what the costs are, and virtually impossible if we don't.

THE IRIDIUM LESSON

- In many respects Iridium was a technical success and a business failure
  - Built and launched a large number of satellites in dramatically less time than had been done before
  - Showed that large LEO constellations were indeed technically feasible
  - Had some technical problems, but overall the space system worked
- We should not take comfort in this result
  - It did not meet the fundamental need of those who paid for it to generate sufficient income to offset cost
  - Many of the problems were in worldwide licensing and manufacture of the ground units (i.e., the satellite telephones)
  - It did not anticipate the rapid growth of terrestrial cellular communications and customer expectations
- In a sense, what failed was the mission utility analysis and mission implementation

If constellations are to be successful, they must meet the needs of whoever pays for them in terms of both performance and cost.

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SUMMARY: THE DRIVING REQUIREMENTS FOR CONSTELLATION DESIGN AND MANAGEMENT

- **Schedule compression**
  - **Long delays are deadly when billions have been spent with no return on investment or science data**
  - **This does not imply a demand to shorten up-front system and mission engineering**
    - **Early delays may be necessary to ensure funding**
    - **Gives time to plan carefully and look for cost reduction options**

- **Flexibility**
  - **In all aspects, flexibility to accommodate change has a high value**
    - **Growth and degradation plateaus**
    - **Large margins to drive down operations cost and complexity**
    - **Do as much on-board with software as possible—its the only "on-orbit replaceable unit" for most constellations**
  - **Use "simple" software, with large margins for growth**

- **Motion relative to other satellites within and outside the constellation is critical**
  - **Key problem areas:**
    - **Collision avoidance within the constellation**
    - **Collision avoidance with satellites or debris outside the constellation**
    - **RF interference with other satellite systems (LEO, MEO, and GEO)**
  - **Advance knowledge or advance warning significantly reduces the cost and complexity of solving these problems**

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Space Mission Engineering

THE DRIVING REQUIREMENTS FOR CONSTELLATION DESIGN AND MANAGEMENT (CONT.)

- **Constellation management is a key cost and performance driver**
  - **"Spacecraft are just tall telephone poles" is great for conceptual business planning, but remember that each "pole" is complex, needs attention, and is moving at 7.5 km/sec relative to the user and to each other**
- **The need for strong collision avoidance may impact coverage and requires consideration during deployment, rephasing, and satellite replacement**
- **When you're done, dispose of it safely**
- **Make sure the constellation design supports the business plan—i.e., is the mission utility worth the cost**

Like any system, all of the components of a constellation must work and must work together to satisfy the needs of the user:

- **The satellites**
- **The constellation**
- **The ground segment and operations**
- **The user interface**
- **The business plan or operations concept**

- **It is the IS&T community's role to help ensure that this happens.**